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# Impact of deposition on the enrichment of organic carbon in eroded sediment

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## Abstract

A substantial part of eroded material can be deposited along the runoff pathway. This deposition process may alter the composition of the transported material. Topography- and vegetation-induced deposition processes were examined under laboratory conditions and at the hillslope and watershed scale. The laboratory experiments showed that the enrichment ratio of the specific surface area, $ER_{SSA}$, of the transported sediment followed an exponential increase with decreasing sediment delivery ratio, SDR, regardless of the type of deposition process. However, the increase in $ER_{SSA}$ with decreasing SDR values was lower than expected. The upper limit of the $ER_{SSA}$ was estimated to be 1.66, which is much lower than the calculated theoretical upper limit of 5.22. This difference can be attributed to the transport of the eroded material in micro-aggregated form. It was also found that the specific surface area, SSA, is a good predictor of organic carbon, OC. The observations on field plots confirmed the results of the laboratory experiments. Measurements at the watershed level indicated that the intensity of the erosion process had a more important influence on sediment enrichment, while the impact of deposition tended to be rather limited. However, sediment monitoring over a longer period is required to reveal the importance of the different erosion processes with regard to OC losses at the field and watershed level.

Keywords: Deposition; Sediment delivery ratio; Enrichment ratio; Organic carbon

## 1. Introduction

Losses of organic carbon, OC, are strongly associated with transport of eroded sediment. Deposition of eroded material by topography and vegetation will also result in a redistribution of the transported OC. However, deposition is a selective process where coarser and heavier particles settle out more easily than the finer fraction (e.g. Davis et al., 1983; Lu et al., 1988; Beuselinck, 1999). Because the finer particles are relatively enriched in organic matter, deposition may alter the composition of the transported sediment compared to the original soil. However, the eroded sediment not only consists of primary particles. Clay particles and OC are mainly transported in aggregated form (Alberts et al., 1980; Young, 1980), which results in more deposition of clay and OC and less enrichment of these components in the transported sediment.

The enrichment of OC due to deposition of eroded sediment is particularly important from a soil conservation's point of view. Erosion control measures like grass buffer strips are based on trapping the eroded sediment in order to diminish off site effects of erosion. Several studies have proven that grass buffer strips can reduce OC losses (e.g. Bingham et al., 1980; Srivastava et al., 1996). On the other hand, Daniels and Gilliam (1996) and Le Bissonnais et al. (2004) found that the sediment transported through grass and riparian strips was enriched in silt and clay. Therefore, these control measures may reduce OC losses less efficiently compared to total sediment losses, due to the selective nature of the deposition process.

The importance of deposition compared to other enrichment processes like interrill erosion, is still unclear. Di Stefano and Ferro (2002) stated that apparently conflicting results reported in literature, are probably explained by the difficulty of separating the effects of in situ selectivity of the erosion processes from preferential deposition during the conveyance process.

Since in case of deposition, enrichment is mainly influenced by the deposition rate of larger particles, enriching the amount of smaller particles in suspension, the sediment delivery ratio, SDR, is frequently used to predict the enrichment ratio ER of suspended soil constituents (e.g. Di Stefano and Ferro, 2002). ER is defined as the ratio of the content of a soil constituent in the eroded sediment to its content in the original soil, whereas SDR is the ratio between the sediment output and the sediment input. In literature, no equations are given which directly relate SDR to enrichment of OC. However, transport of soil adsorbed constituents such as OC can be estimated by assuming that the concentration of the constituent is directly proportional to the specific surface area, SSA, of the mineral soil fraction (Young and Onstad, 1976; Storm et al., 1988). Therefore, SSA can be a useful index to determine enrichment of sediment adsorbed elements (Foster et al., 1985; Sharpley, 1985).

Based on simulations with the CREAMS model, Foster et al. (1985) found that it was not the type of deposition process that influenced the enrichment process, but rather the soil texture. They suggested the following equation for a silt loam soil:

$$ER_{SSA} = 1 + 3.63 \exp(-14.8\ SDR) \qquad (1)$$

and for a loam soil:

$$ER_{SSA} = 1 + 3.41 \exp(-7.40\ SDR) \qquad (2)$$

Considering an exponential decreasing function as found by Foster et al. (1985) and assuming that the enrichment ratio of SSA, $ER_{SSA}$, becomes 1 if SDR reaches 1, $ER_{SSA}$ can be related to SDR by using the following "general exponential equation":

$$ER_{SSA} = 1 + (ER_{SSA,ul} - 1) \exp(-b\ SDR) \quad (3)$$

where b is a regression parameter, and $ER_{SSA,ul}$ the upper limit of the $ER_{SSA}$, i.e. for SDR values reaching 0.

The overall objective of this study was to examine the enrichment of OC in transported sediment in relation to topography- and vegetation-induced deposition. In order to address this objective, we conducted laboratory experiments (1) to evaluate Eq. (3) for the soil under study and to compare it with Eqs. (1) and (2), and (2) to relate $ER_{OC}$ directly to SDR. Those findings were then (3) verified using data collected at the hillslope and the watershed scale.

## 2. Materials and methods

### 2.1. Laboratory experiments

#### 2.1.1. General

The soil used in the laboratory experiments was a silt loam, which was collected (0-0.05 m depth) at field plots situated at Maarkedal, Belgium (50°46'29'' N, 3°35'11'' E). The soil contains 170 g $kg^{-1}$ clay, 540 g $kg^{-1}$ silt, 290 g $kg^{-1}$ sand and 11 g $kg^{-1}$ OC. The soil pH (KCl) (1:2.5 (w/w)) was 5.4 and it did not contain $CaCO_3$.

Four series of experiments were carried out under laboratory conditions, and are described below.

#### 2.1.2. Series #1: Addition of water and sediment to a non-erodible flume

A non-erodible, plastic V-shaped flume, with a length of 1.6 m and an inner angle of 90° was used. The flume was set at slopes of 2, 3, 5, 7, 8 and 10%. At the upper edge of the flume, tap water and air-dried soil aggregates (< 2 mm) were added at a constant discharge of

0.01 l $s^{-1}$ and with a sediment concentration of 163 g $l^{-1}$. The experiments lasted for 10 min. The runoff volume was measured every 60 s and analyzed for sediment content. The final runoff sample was also analyzed for OC content and texture, which was also done for the sediment deposited in the flume during the whole experiment.

### 2.1.3. Series #2: Addition of water and sediment to a preformed erodible gully

A soil pan (0.96 m long, 0.56 m wide and 0.20 m deep) was filled with air dried soil aggregates (< 8 mm) to obtain a bulk density of 1.33 Mg $m^{-3}$. An artificial rill was made with slopes of 30% at both sides. The soil pan was placed at slopes of 3, 5, 10, 20 and 30%. Tap water and air-dry aggregates (< 2 mm) were added at a constant discharge of 0.01 l $s^{-1}$ and 0.017 l $s^{-1}$ at the upper edge of the rill. The average input sediment concentration was 163 g $l^{-1}$. Runoff volume was measured and analyzed for sediment content every 60 s in case of the low discharges and every 30 s in case of the high discharges. The final runoff sample and the sediment deposited during the whole experiment were analyzed for OC content and texture. Every experiment lasted for 5 and 10 min for the high and low runoff discharges respectively.

### 2.1.4. Series #3: Rainfall simulation on a preformed erodible gully

The experimental setup was similar to the setup of series #2, except that neither water nor sediment was added to the rill. Instead of this, rainfall simulations were carried out in the I.C.E. wind tunnel (International Centre for Eremology, Ghent University, Belgium; see Gabriels et al., 1997; Cornelis et al., 2004a), using intensities of 100 mm $h^{-1}$. Kinetic energy of the rainfall was measured using the splash-cup technique (e.g. Ellison, 1947; Salles and Poesen, 2000; Cornelis et al., 2004b,c). The soil pan was set at slopes of 2, 3, 5, 10, 20 and 30%. The duration of each rainfall simulation was 30 minutes. Runoff discharge was measured continuously and every 30 s, samples were taken for analysis of sediment concentration. The final runoff sample and sediment deposited during the whole experiment were analyzed for OC content and texture

### 2.1.5. Series # 4: Addition of water and sediment to grass strips

Soil aggregates (< 2 mm) were mixed with water and directed in a non-erodible rectangular shaped plastic flume (0.14 m wide and 2 m long). The lower 0.8 m of the flume was filled with a grass strip (grass height was on average 0.10 m) taken at the experimental fields at Maarkedal, Belgium. The runoff discharge was set equal to 0.017 l $s^{-1}$ and 0.022 l $s^{-1}$. Slopes of 5, 10 and 20% were used. Runoff and sediment discharge were measured continuously. The final runoff sample and sediment deposited during the whole experiment were analyzed for OC content and texture.

## 2.2. Field Measurements at the hillslope scale

The experimental field at Maarkedal (50°46’29’’ N, 3°35’11’’E), Belgium, was subdivided in five replicate plots, each 100 m long and 1 m wide. Soil properties are given above. On the field, grain maize was sown after conventional tillage (moldboard ploughing followed by harrowing). Grass strips with different lengths (0, 1, 2, 5 and 10 m) were laid down at the lower edge of the plots. Runoff discharge was measured continuously with a tipping bucket system and a flow-proportional mixed sample was collected for every field plot. After an intense rainstorm on 23 July 2001, with a total rainfall amount of 67 mm and a maximum rainfall intensity of 80 mm $h^{-1}$ (during 5 min) runoff samples from the Maarkedal field plots were collected and analysed for OC and texture.

## 2.3. Measurements at the watershed scale

During several rainfall events, water samples were collected at the outlet of two rural watersheds (0.1 and 2.7 km$^2$) at Maarkedal (Belgium). In the smallest one (0.1 km$^2$) only arable, conventionally tilled fields occur. This watershed is part of the 2.7 km² watershed, of which 46 % consists of arable land, 31 % is grassland, 3 % is woodland and 20 % is urban. Soil sampling (0-5 cm depth) was conducted in both watersheds to determine the OC status (Table 1). In Table 1 only sampling data of arable fields are given because the soil loss from grassland is negligible, due to the dense grass vegetation.

## 2.4. Analysis of samples and data

The particle-size distribution of the original soil, the sediment in the runoff samples as well as the deposited sediment was obtained using the sieve pipette method (De Leenheer, 1966) after complete dispersion of the samples. These data were then used to determine SSA of the soil and sediment and hence $ER_{SSA}$. SSA was calculated according to:

$$SSA = Sa\, SSA_{Sa} + Si\, SSA_{Si} + Cl\, SSA_{Cl} \quad (4)$$

where Sa, Si and Cl are the fractions (g g$^{-1}$) of sand, silt and clay respectively, and $SSA_{Sa}$, $SSA_{Si}$ and $SSA_{Cl}$ are the SSA (m$^2$ g$^{-1}$) for sand, silt and clay respectively. Foster et al. (1985) proposed 0.05, 4 and 20 m$^2$ g$^{-1}$ as values for the SSA of sand, silt and (kaolinitic) clay respectively. According to Yong and Warkenton (1966), illite and montmorillonite have an approximate SSA of 80 and 800 m$^2$ g$^{-1}$, respectively. Talibudeen (1981) mentioned $SSA_{Cl}$ values for illite ranging between 90 and 130 m$^2$ g$^{-1}$, while Sposito (1984) used an average value of 112 ± 5 $m^2$ $g^{-1}$. Because illite is the dominant clay mineral in our soil, we set $SSA_{Cl}$ equal to 100 $m^2$ $g^{-1}$. Analysis of the results showed, however, that the choice of the $SSA_{Cl}$ value had almost no influence on the calculated $ER_{SSA}$ values.

The sediment concentration of the runoff samples was determined by weighing the oven-dried (at 105 °C) tarred recipients, and enabled to calculate SDR. To determine $ER_{OC}$, we measured OC using the method of Walkley and Black (1934). Because this method yields on average 75 % of the total OC, the results of the analysis were divided by 0.75 to obtain the total OC content (De Leenheer and Van Hove, 1958). $ER_{SSA}$ and $ER_{OC}$ were calculated by respectively dividing SSA and OC in the sediment by SSA and OC in the original soil material.

Analysis of variance and regression analysis were executed using the statistical software package SPSS v11.0.1 (SPSS Inc., 2001). Equations (1), (2) and (3) were evaluated using SSA data from the runoff samples on the one hand, and on the other hand using SSA data from the deposited sediment. In the latter case, we calculated for every timestep i of each experiment, i.e. the runoff sampling interval, the SSA as predicted from the difference between the total input and output of SSA according to:

$$(1 - SDR_i)\, Qin_{s,i}\, SSA_{dep,i}\, t_i = SSA_{soil}\, Qin_{s,i}\, t_i - SSA_{soil}\, Qin_{s,i}\, ER_{SSA,i}\, SDR_i\, t_i \qquad (5)$$

where $Qin_{s,i}$ is the input sediment discharge (g $s^{-1}$), $SSA_{dep,i}$ is the SSA of the deposited sediment ($m^2$ $g^{-1}$), i is the timestep and $t_i$ its duration (s). $ER_{SSA,i}$ is calculated using Eqs. (1), (2) or (3). Summation for all the timesteps, and dividing by the total amount of deposition, results in the SSA of the deposited sediment, $SSA_{dep}$. The predicted $SSA_{dep}$ values were compared with the measured $SSA_{dep}$ by calculating the root mean square error, RMSE, and the coefficient of residual mass, CRM, which are respectively defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(SSA_{dep,i} - \hat{SSA}_{dep,i})^2}{n}} \tag{6}$$

and

$$CRM = \frac{\sum_{i=1}^{n} SSA_{dep,i} - \sum_{i=1}^{n} \hat{SSA}_{dep,i}}{\sum_{i=1}^{n} SSA_{dep,i}} \tag{7}$$

where n is the number of samples. The RMSE gives the average difference between calculated and measured data, while the CRM indicates whether the calculations overestimate (CRM < 0) or underestimate (CRM > 0) the measurements. The optimum value for both statistical parameters is zero.

## 3. Results and discussion

### 3.1. Laboratory experiments

In Fig. 1, $ER_{SSA}$ is plotted against SDR of the last sampling interval for all experiments except those at a slope of 10% in case of the series #1 experiments, and at slopes of 10, 20 and 30% in case of the series #2 and #3 experiments. At those relatively high slopes, deposition did not occur. As can be seen, $ER_{SSA}$ varies between 1 and 1.5, and is decreasing with increasing SDR. Factors such as roughness (non-erodible flume vs erodible gully), rainfall impact (watering vs simulated rainfall) or the presence of a sediment trap (bare surface vs. grass buffer) did not additionally affect $ER_{SSA}$. This is supported by findings of

Foster et al. (1985) who found that, using the CREAMS model, $ER_{SSA}$ for a given SDR did not depend on the type of deposition process, but on the sediment characteristics (see Eqs. (1) and (2)).

Equation (3) was fitted to the data in Fig. 1, with $ER_{SSA,ul}$ taken as its theoretical value, assuming that at very low SDR values only clay is transported. Accordingly, the theoretical upper limit of the $ER_{SSA}$, $ER_{SSA,ul\_t}$ can be defined as the ratio between $SSA_{Cl}$ and SSA of the original soil ($m^2 g^{-1}$). Considering an illite clay type with an $SSA_{Cl}$ of 100 $m^2 g^{-1}$, $ER_{SSA,ul\_t}$ is, according to Eq. (4) and the texture data of the original soil, equal to 5.22. This resulted in following equation for $ER_{SSA}$:

$$ER_{SSA} = 1 + 4.22 \exp(-5.78\ SDR) \qquad (8)$$

Figure 1 shows that Eq. (8) deviates from the measured data. At low SDR values, Eq. (8) strongly overestimates the measurements. The soil used in our experiments has a silt loam texture, but close to the loam textural class. It can be seen that Eq. (1), proposed by Foster et al. (1985) for silt loam soils, slightly underestimates $ER_{SSA}$ between 0.2 and 0.8. On the other hand, Eq. (2), proposed by Foster et al. (1985) for loam soils slightly overestimates $ER_{SSA}$ at low SDR values, but to a lesser extent than Eq. (8). According to Eqs. (1) and (2), the upper limit of $ER_{SSA}$, $ER_{SSA,ul}$, equals 4.63 and 4.41 respectively.

Setting $ER_{SSA,ul}$ as a free fitting parameter in Eq. (3) in:

$$ER_{SSA} = 1 + 0.663 \exp(-2.454\ SDR) \qquad (r = 0.887) \qquad (9)$$

This means that $ER_{SSA,ul}$ equals 1.663, which is significantly lower than the theoretical upper limit of 5.22 and the $ER_{SSA,ul}$ values of 4.63 and 4.41. Figure 1 shows that the largest differences between Eqs. (1), (2) and (9) are observed for SDR values below 0.2. At these low SDR values, the determination of the SSA of the eroded sediment is rather difficult due to the low sediment concentration in the runoff. Therefore, we verified Eqs. (1), (2) and (9) by comparing SSA, predicted by Eqs. (1), (2) and (9) respectively, with the measured SSA of the sediment deposited during the whole experiment, using Eq. (5). The results in Table 2 show that Eq. (2) fits the $SSA_{dep}$ values slightly better than the other equations. On the other hand, Eqs. (1) and (2) result, on average, in an overestimation of the $SSA_{dep}$ values, while Eq. (9) slightly underestimates the observations. Based on the results in Fig. 1 and Table 2, we can conclude that Eq. (9) agrees best with our observations.

Figure 2 shows $ER_{OC}$ as a function of SDR. Also shown are Eqs. (1), (2) and (9). The $ER_{OC}$ values are more scattered than the $ER_{SSA}$ values, but Eqs. (1), (2) and (9) fit the data quite well, indicating that OC is closely related to SSA of the eroded sediment. Non linear regression resulted in:

$$ER_{OC} = 1 + 1.931 \exp(-5.367\ SDR) \qquad (r = 0.828) \qquad (10)$$

Based on the measured OC in the deposited sediment, Eqs. (1), (2), (9) and (10) were compared using Eq. (5), like it was done for the SSA values (see Table 3). On average, all equations overestimate OC in the deposited sediment. Equation (9) resulted in the best fit, even better than Eq. (10). Although more experimental work is needed to determine more accurately the $ER_{SSA}$ and $ER_{OC}$ values at low SDR, the results indicate that the upper limits of $ER_{SSA}$ and $ER_{OC}$ are probably lower than the theoretical values and the values proposed by Foster et al. (1985). This may be attributed to the transport of mineral particles and OC in aggregated form, rather than as individual particles. Comparing the dispersed and undispersed particle size distribution, Schiettecatte et al. (submitted) found that the clay particles of the soil used in this study, form small aggregates (2-10 µm). In this way, deposition of aggregates will reduce the amount of clay and OC in suspended material considerably. Therefore, deposition may be more selective in transport of primary particles, rather than transport of aggregates. Beuselinck (1999) examined the transport of soil aggregates over an area of net deposition and found that deposition is only slightly size selective if the transported sediment mainly consisted of aggregates: the dispersed size distribution of the inflow sediment and that of the deposited material were very similar. Beuselinck et al. (2000) analysed topography- and vegetation-controlled sediment deposits in two small watersheds. Although significant differences in aggregate size were found, the dispersed particle-size distributions and OC contents of both types of sediment were similar. Furthermore, they found no significant difference between the dispersed particle size distribution of the sediment deposits and the source material. Beuselinck et al. (2000) also separated different aggregate classes of the source material by dry sieving, and determined their dispersed particle size distribution: all aggregates had a similar textural composition, which was comparable to that of the original soil. In our study, a similar result was found for the dry sieved aggregate classes (Table 4). The OC content of the different classes is also comparable to that of the original soil. This confirms the equal distribution of OC within the soil aggregates, like it also was observed after wet sieving (Schiettecatte et al., submitted). Because the aggregate classes have a similar OC content and textural composition, relatively large amounts of OC and fine particles are trapped by deposition, regardless of the aggregate size distribution of the deposited material. As a consequence, the enrichment effect of the deposition process is rather limited in our study. Other researchers, however, have shown that the OC content of aggregate classes can differ significantly (Ghadiri and Rose, 1991; Wan and El-Swaify, 1997; 1998), which can affect the enrichment process.

Polyakov and Lal (2004) conducted rainfall simulations on small soil pans (0.3 m wide and 1 m long) filled with sieved (< 8 mm) silt loam soil. Four soil pans were positioned in a cascade system in which runoff from the upper soil pan flowed into the lower pan. The subsequent pans were put under different slopes (8, 7, 1 and 0.5 % respectively), resembling a concave slope. This setup resulted in deposition of sediment from the 7 % slope on the 1 % slope. Polyakov and Lal (2004) published the average values of three replicated experiments (Table 1 in Polyakov and Lal, 2004), which are given in Table 5. The sediment discharge data from the 7 % and 1 % slope were used to calculate the SDR in order to validate the $ER_{OC}$ values calculated by Eqs. (1), (9) and (10) respectively. Table 5 shows that the $ER_{OC}$ values calculated using Eq. (9) have the best agreement with the $ER_{OC}$ values based on the observations of Polyakov and Lal (2004). The other equations underestimate the observed $ER_{OC}$ values. This indicates that at high SDR values (> 0.5), the eroded sediment is slightly enriched in OC. Summarizing, our results indicate that at low SDR values, the enrichment is smaller than estimated by Eqs. (1) and (2). On the other hand, at high SDR values, there is still a slight enrichment of the eroded material, being larger than estimated by Eqs. (1) and (2). Overall, however, the enrichment of eroded material by deposition is rather limited, with ER values mainly varying between 1 and 1.5.

### 3.2. Field experiments at the hillslope scale

For the plots with different grass strip lengths, the ER was calculated based on the ratio of the SSA or OC concentration in the eroded sediment and its corresponding concentration in the eroded sediment from the reference field, i.e. without grass strip. The differences in grass strip length resulted in different SDR values for the field plots. The ER values in Fig. 3 reveal a similar trend as found for the laboratory experiments: Eq. (9) better fits the data than Eq. (10). This confirms the rather unselective nature of the deposition process, as it was also observed in the field by Beuselinck et al. (2000).

## 3.3. Measurements at the watershed scale

The watershed scale measurements allowed verifying the importance of the enrichment mechanism of the erosion and deposition processes at a larger scale. In Fig. 4, the OC content of the sediment in the runoff samples is shown as a function of sediment concentration. The sediment concentration gives an indication of the intensity of the erosion process occurring within the watershed. Much higher OC contents can be observed in the large watershed compared to the small one, although the average OC contents of the soils within both watersheds are similar (Table 1). This indicates that at a larger scale, the sediment became more enriched in OC, due to the increased probability of sediment deposition by topography and vegetation. On the other hand, the enrichment may be explained by the different sampling periods. The samples in the small watershed were taken during an intense rainstorm in June, while the large watershed was sampled during long lasting, low intensity rainfall events in December. The former may have caused unselective erosion, while the latter may have resulted in more selective interrill erosion processes.

Le Bissonnais et al. (1998) found that for sediment concentration, the scale ratio between plots and catchments is systematically below 1 due to sediment deposition along the route from field to catchment outlet. According to Walling (1983), sediment export typically accounts for only 10 % of the soil displaced over an eroding landscape, which suggests that deposition within the watershed may become a more important enrichment mechanism when scale increases. Avnimelech and McHenry (1984) determined the OC content in the sediments of 41 impoundments and in the soils of the contributing watersheds, varying in size between 0.06 and 274.5 km$^2$. Based on these analyses, the $ER_{OC}$ was determined. They observed $ER_{OC}$ values between 0.24 and 6.3, with 80% between 0.43 and 1.83. The $ER_{OC}$ values were not related to the size of the watershed, which puts into perspective the importance of deposition on the enrichment of exported sediment. For small watersheds (< 0.01 km$^2$), the $ER_{OC}$ values reported by Jacinthe et al. (2004) and Owens et al. (2002) varied mostly between 1 and 1.9. Weigand et al. (1998) determined the $ER_{OC}$ values in 8 watersheds, 0.02 to 0.18 km$^2$ large. The $ER_{OC}$ ranged between 0.52 and 4.58, with 80% of the samples between 1.6 and 2.2. The data from these small watersheds were obtained over a one year monitoring period, in which low and high intensity storms occurred.

When considering the importance of rainfall intensity, Jacinthe et al. (2004) observed a higher OC content in the sediments transported during low-intensity storms than in the material displaced during high-intensity storms. This was also found by Quinton et al. (2001) for particulate phosphorus losses. The occurrence of low intensity storms in the above mentioned studies for small watersheds (Weigand et al., 1998; Owens et al. 2002; Jacinthe et al., 2004) may explain the stronger enrichment in OC compared to our data from the small watershed of 0.1 km$^2$, which were obtained during a high intensity rainfall event. Therefore, the intensity of the erosion process may be a more important factor in the enrichment process than the deposition within the watershed. This also agrees with the laboratory measurements of Schiettecatte et al. (submitted), where higher $ER_{OC}$ values (up to 2.61) were observed for interrill experiments than we found in our deposition experiments. However, in order to point out which of both factors, scale or rainfall event, is the most important, a more intensive monitoring of runoff and sediment is needed.

## 4. Conclusions

Topography- and vegetation-induced deposition processes were examined in laboratory rainfall and flume experiments. These experiments showed that the $ER_{SSA}$ of the transported sediment followed an exponential decrease with increasing SDR, regardless of the type of deposition process. However, the increase in ER with decreasing SDR values was lower than expected, which can be attributed to the transport of the eroded material in micro-aggregated form. More experiments at low SDR values are needed to confirm these results. It was also found that the SSA is a good predictor of OC. The observations on field plots confirmed the results of the laboratory experiments. Measurements at the watershed level indicated that, with respect to sediment enrichment, the intensity of the erosion process may be more important than deposition. However, sediment monitoring over a longer period is required to reveal the importance of the different erosion processes with regard to OC losses at the field and watershed level.

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**Table**
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Table 1. Results of the organic carbon, OC, sampling survey on arable fields in the studied watersheds

| Watershed area (km$^2$) | Number of samples | OC content (g kg$^{-1}$) | | |
|---|---|---|---|---|
| | | Mean | Median | Range |
| 2.7 | 53 | 13.4 | 12.2 | 7.5 – 52.5 |
| 0.1 | 5 | 10.8 | 11.0 | 9.7 – 12.0 |

Table 2. The root mean square error, RMSE, and coefficient of residual mass, CRM, based on the measured specific surface area, SSA, in the deposited sediment and the SSA values calculated with Eqs. (1), (2) and (9)

| Equation number | RMSE | CRM |
|---|---|---|
| 1 | 3.62 | -0.20 |
| 2 | 2.76 | -0.11 |
| 9 | 3.36 | 0.02 |

Table 3. The root mean square error, RMSE, and coefficient of residual mass, CRM, based on the measured OC values in the deposited sediment and the OC values calculated with Eqs. (1), (2), (9) and (10)

| Equation number | RMSE | CRM |
|---|---|---|
| 1 | 0.29 | -0.44 |
| 2 | 0.24 | -0.33 |
| 9 | 0.18 | -0.17 |
| 10 | 0.21 | -0.31 |

Table 4. Concentration (g $kg^{-1}$) of different particle size fractions and OC in several aggregate classes obtained after dry sieving

| aggregate class (mm) | 0-2 μm | 2-10 μm | 10-20 μm | 20-50 μm | 50-2000 μm | OC |
|---|---|---|---|---|---|---|
| 0.3-0.5 | 175 | 52 | 114 | 381 | 278 | 12 |
| 0.5-1 | 179 | 57 | 109 | 376 | 278 | 11 |
| 1-2 | 175 | 56 | 120 | 357 | 291 | 11 |
| 2-8 | 173 | 47 | 125 | 379 | 276 | 9 |
| 0-8[a] | 170 | 48 | 112 | 380 | 290 | 11 |

[a] The aggregate class 0-8 mm corresponds to a bulk sample of the original soil, which was eventually ground to smaller aggregates (< 2 mm) to be used in the experiments

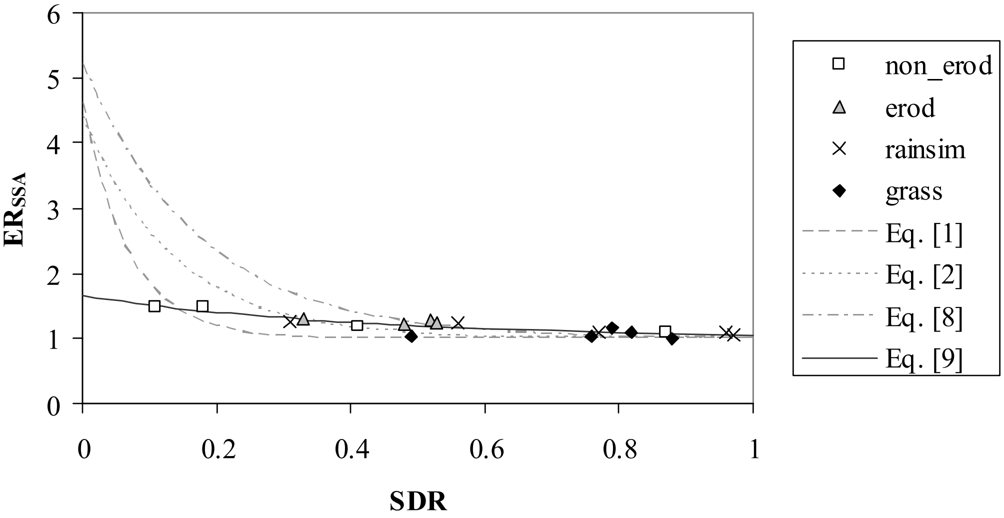
Table 5. Validation of $ER_{OC}$ values calculated by Eqs. (1), (9) and (10), with data published by Polyakov and Lal (2004)

| sediment discharge[a] (g min$^{-1}$) | | SDR | OC content (g kg$^{-1}$) of transported sediment[a] | | $ER_{OC}$ | calculated $ER_{OC}$ | | |
|---|---|---|---|---|---|---|---|---|
| slope 7% | slope 1% | | slope 7% | slope 1% | | Eq. (1) | Eq. (9) | Eq. (10) |
| 6.18 | 5.34 | 0.86 | 23.4 | 26.5 | 1.13 | 1.00 | 1.08 | 1.02 |
| 14.19 | 7.08 | 0.50 | 18.8 | 23.1 | 1.23 | 1.00 | 1.19 | 1.13 |
| 14.83 | 9.12 | 0.61 | 17.9 | 21.8 | 1.22 | 1.00 | 1.15 | 1.07 |
| 14.03 | 8.81 | 0.63 | 18.7 | 21.9 | 1.17 | 1.00 | 1.14 | 1.07 |

[a] data published by Polyakov and Lal (2004)

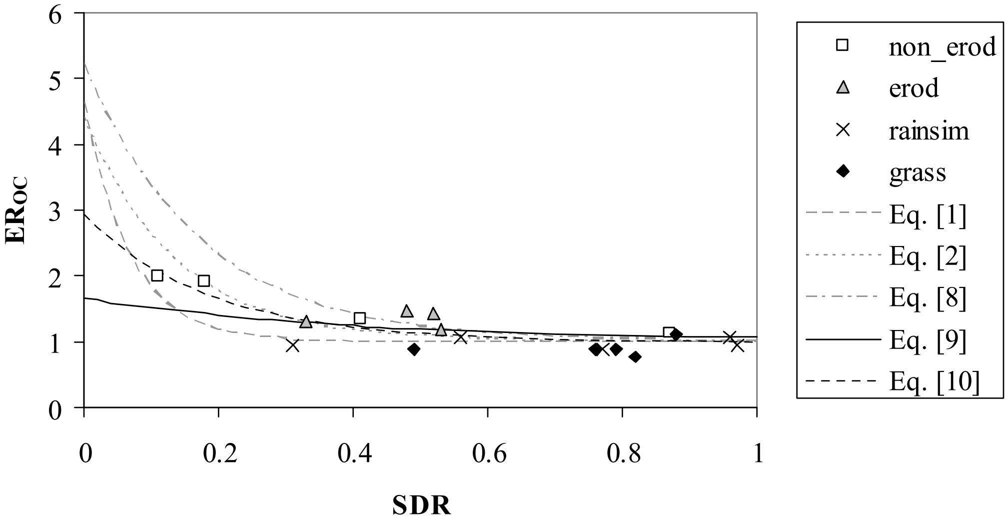
**Figure**

Fig. 1.



6
5
4
3
2
1
0
ER$_{SSA}$
0
0.2
0.4
0.6
0.8
1
SDR
non_erod
erod
rainsim
grass
Eq. [1]
Eq. [2]
Eq. [8]
Eq. [9]

Fig. 2.



6
5
4
3
2
1
0
ERoc
0
0.2
0.4
0.6
0.8
1
SDR
non_erod
erod
rainsim
grass
Eq. [1]
Eq. [2]
Eq. [8]
Eq. [9]
Eq. [10]

Fig. 3. The $ER_{OC}$ and $ER_{SSA}$ as a function of SDR for the field plot experiments with grass strips

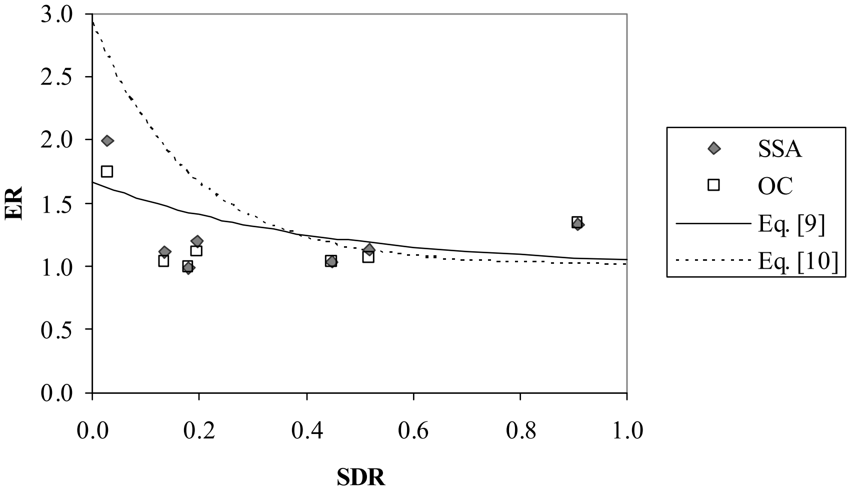


Fig. 4. The OC content versus sediment concentration of the samples taken at the outlet of the watersheds of 0.1 and 2.7 $km^2$

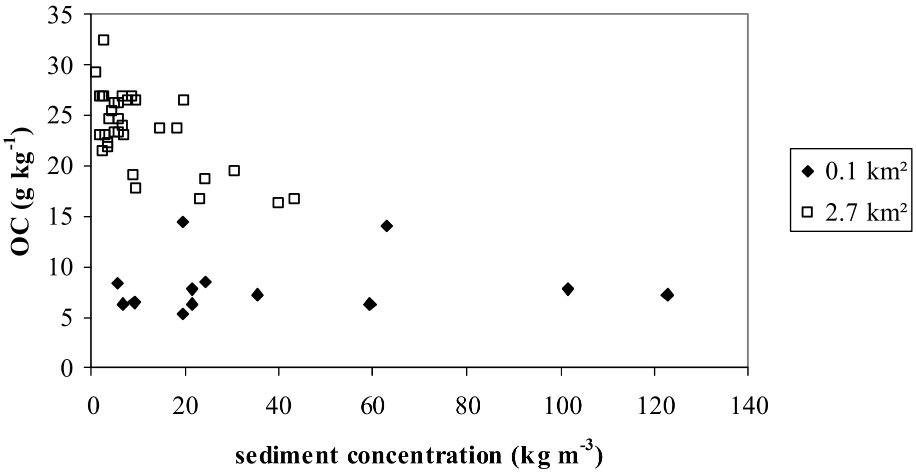


Fig. 1. The enrichment ratio of the specific surface area, $ER_{SSA}$, as a function of sediment delivery ratio, SDR, for the deposition experiments in a non-erodible flume (non_erod), an erodible gully (erod), under rainfall simulation (rainsim) and with grass strips (grass)

Fig. 2. The enrichment ratio of OC, $ER_{OC}$, as a function of SDR for the deposition experiments in a non-erodible flume (non_erod), an erodible gully (erod), under rainfall simulation (rainsim) and with grass strips (grass)

Fig. 3. The $ER_{OC}$ and $ER_{SSA}$ as a function of SDR for the field plot experiments with grass strips

Fig. 4. The OC content versus sediment concentration of the samples taken at the outlet of the watersheds of 0.1 and 2.7 $km^2$